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OPTICAL INTERFEROMETER IN SPACE

P. L. Bender,* J. E. Faller,* J. L. Hall,* D. Hils, R. T. Stebbins and M. A. Vincent**

Joint Institute for Laboratory Astrophysics

University of Colorado and National Institute of Standards and Technology

Boulder, Colorado 80309

ABSTRACT

The present design concepts for a Laser Gravitational-Wave Observatory in Space are described. Laser heterodyne distance measurements are made between test masses located in three spacecraft separated by roughly 10^6 km. The major technology issues are: the reduction of spurious acceleration noise for the test masses to below 2×10^{-15} cm/sec^2/Hz$^{0.5}$ from 10^{-5} to 10^{-3} Hz; and the measurement of changes in the difference of the antenna arm lengths to 5×10^{-11} cm/Hz$^{0.5}$ from 10^{-3} to 1 Hz with high reliability. The science objectives are: to measure discrete sinusoidal gravitational wave signals from individual sources with periods of 1 second to 1 day; to measure the stochastic background due to unresolved binaries; and to search for gravitational wave pulses with periods longer than 1 second from possible exotic sources such as gravitational collapse of very massive objects.

1) INTRODUCTION

It seems likely that several of the proposals in different countries for large ground-based laser gravitational wave detectors will be funded in the next 2 or 3 years. If so, the prospects appear good for the direct detection of gravitational wave signals within a decade. However, the sensitivity which can be achieved in ground-based detectors at frequencies below about 10 Hz is strongly limited by environmental noise sources. Even if complete isolation of the test masses from ground motions is possible, the gravity gradient noise due to naturally occurring density variations in the ground and atmosphere would cause the instrumental strain sensitivity to get worse as roughly the inverse fourth power of the frequency (Saulson 1984).

Since a number of types of gravitational wave sources which may provide unique kinds of astrophysical information exist only at frequencies below 1 Hz, we have carried out studies of the sensitivity which could be achieved at frequencies of 10^{-5} to 1 Hz with a three-satellite interferometric antenna for a Laser Gravitational-Wave Observatory in Space (LAGOS). A lot more work is needed, particularly on methods for minimizing the time-varying spurious acceleration of the test mass in each spacecraft at periods from 10^{-5} to 10^{-3} Hz. However, the general characteristics of the LAGOS antenna design (Stebbins et al. 1988) and the types of gravitational wave sources which could be observed with it (Hils et al. 1986) have become fairly well established. The antenna design characteristics are described briefly in this article, with particular emphasis on the problem of reducing spurious accelerations of the test masses at frequencies of 10^{-5} to 10^{-3} Hz.

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* Staff member, Quantum Physics Division, National Institute of Standards and Technology

** Now at: Jet Propulsion Laboratory, Pasadena, CA 91109

2) *Basic Antenna Design*

Our present baseline case for the LAGOS antenna location and geometry are shown in Fig. 1. The three spacecraft are located about 30° behind the Earth in orbit around the sun. The center one is in a circular orbit with one year period. By choosing the orbits for the other two correctly, one can achieve a right-angle geometry, with the two end spacecraft keeping nearly constant and equal distances of roughly 10^6 km from the center one (Faller and Bender 1984). They will appear to go around the center spacecraft with one year period in a plane which is tipped 60° with respect to the ecliptic.

In the absence of planetary perturbations, the variations in the arm lengths would have amplitudes of 0.16% for 10^6 km arm lengths. The largest planetary perturbations are the resonance ones due to the Earth. Computer calculations of these have been carried out by Vincent, and maximum variation of ±0.6% over a ten year period were found. This corresponds to a maximum relative velocity of about 1 m/sec.

The test mass in each spacecraft floats freely within a cavity which is designed to produce very little spurious acceleration of the test mass. In the simplest form of the antenna, a beam-splitter would be mounted in the center test mass and a mirror in each end test mass to form an interferometer. However, with 50 cm diameter telescopes used for transmitting and receiving the light, only about 10^{-7} of the transmitted light is received at the far end. Thus this light is sent to a photo-detector after it is received and beat against a small amount of light from a laser in the end spacecraft. The resulting signal is used to phase-lock the laser, and the main part of the laser light is transmitted back to the center spacecraft. This coherent transponder approach, which is common in optical communications systems, is necessary in order to obtain a sufficiently high signal level. The lasers are assumed to be laser diode pumped Nd YAG lasers, with high efficiency, long lifetimes, and about 1 watt of transmitted power at the 530 nm second harmonic wavelength. The lasers are locked tightly to stable Fabry-Perot cavities in order to obtain good short term phase stability.

Back at the center spacecraft, the received beams from the two ends are beat against the local laser to give output signals at the two Doppler frequencies, which correspond to the rate of change of the two arm lengths. These signals can be down-shifted for convenience, filtered with narrow-band tracking filters, and then sent to continuously counting phase meters which record the phase perhaps every 0.1 sec. Digital filtering methods also need to be considered. The desired phase measurement stability is roughly 2×10^{-6} cycle/Hz$^{0.5}$ from 1 to 10^3 sec intervals. Thus care in the design of the phase measurement system and thermal stability in the optical system are necessary. The required data transmission rate back to the Earth is probably not more than 2 kilobits/sec, depending on the amount of auxiliary data needed.

The data analysis method is based on the fact that there are essentially no unknown perturbations of the arm lengths with periods of 10^5 sec or shorter due to the planets, their satellites, or other solar system bodies. Since the spurious accelerations of the test masses will be kept very small, the apparent unmodeled changes in the sum of the length of the two arms can be taken as a measure of the fluctuations in the laser wavelength (Faller et al. 1985). The changes in the difference of the two arm lengths for the interferometer, corrected for the laser wavelength fluctuations, provide the gravitational wave signal. For a small fractional difference in the interferometer arm lengths, the only negative effect of this laser wavelength correction method will be a comparable fractional error in the amplitude and phase of the detected gravitational wave signals.

It has been recognized from the beginning that minimizing spurious accelerations of the test masses would be the main technological challenge in designing the LAGOS antenna. However, there was not time to do more during the Workshop talk than to show a list of the spurious acceleration sources considered and describe a few of them very briefly. Since most of the discussion after the talk was on this topic, and in view of the helpful questions raised by D. B. DeBra, most of the remainder of this brief summary will be devoted to some of the spurious acceleration issues.

3) Time-Varying Spacecraft Mass Attraction

The gravitational potential due to all of the spacecraft except the test mass can be expressed as a spherical harmonic expansion about a point near the center of the test mass cavity. Because of practical construction tolerances and unknown variations in material densities, the coefficients of the different potential terms will have various uncertainties. We can reduce the low degree coefficients to the level allowed by the uncertainties, in order to minimize the gravitational acceleration of the test mass, but at least the second and third degree potential terms will have to be measured in flight and then cancelled out by displacing small compensating masses. The measurements can be made for all of the important terms by displacing the spacecraft with respect to the test mass by programmed offset vectors and observing the resulting changes in the interferometer arm length difference. This is part of the antenna set-up procedure, and may have to be repeated as frequently as each week.

Terms which cannot be determined by the above procedure are the first degree terms. These give test mass accelerations which are independent of the spacecraft position. They would be balanced to the level of 10^{-11} g, which was the design goal at zero frequency for the TRIAD mission, by careful weighing of spacecraft parts and by adjustments. Other potential terms give forces which vary with spacecraft displacement. The effects of such terms would be minimized by servo control of the spacecraft position so that it doesn't move with respect to the test mass by more than 1 micron. This is feasible because the amplitude of solar wind and solar radiation pressure force variations on the spacecraft at the periods of interest will be quite small with respect to the average radiation pressure force.

Two important questions raised by D. B. DeBra concern the spacecraft potential changes caused by fuel motion and by thermal distortion. We have assumed so far that cold gas thrusters using perhaps N_2 would provide the acceleration of roughly 10^{-8} g needed in order to counteract the solar radiation pressure. Preliminary estimates indicate that, for the end spacecraft, the N_2 for a ten year mission could be located in two spherical tanks opposite each other and at 90° to the interferometer arm. However, they would need to be far enough away so that either about half the Shuttle bay would be needed to hold the three LAGOS spacecraft or the tanks would be deployable after launch. The changes in the second degree potential terms due to fuel usage would need to be cancelled out by pre-programmed motions of small compensating masses, but the accuracy requirements on the motion are not severe. For the center spacecraft, the fuel tanks would be along the axis of the spacecraft.

One other possibility would be to use ion thrusters if they have been developed and qualified for other purposes before Phase B studies for a possible laser gravitational wave mission are started, but this cannot be assumed at present.

The second question concerning thermal distortion of the spacecraft is probably best handled by a combination of good thermal design and correction to the received data. The main driver for such distortions will be solar intensity variations with periods of 10^3 to 10^5 sec, coupled with asymmetric thermal properties of the spacecraft. We have previously discussed the use of a two-stage thermal shield for the main optical system of the spacecraft, plus an extra stage for the test mass cavity and the beam-splitter/detector package (Stebbins et al. 1988). Two insulating blankets with roughly fifty layers each would be used in the two-stage thermal shield, with an outer thermal load structure between them and the main instrument package serving as the thermal load for the inner blanket. The main thermal distortion effects are likely to be from the outer blanket and the outer thermal load, rather than from the inner parts of the spacecraft. Fortunately, it appears that the solar intensity fluctuations can be measured well enough so that the transfer function to the difference in antenna arm lengths can be determined and removed from the data.

4) Non-Gravitational Test Mass Perturbations

At very low frequencies, it appears impossible to avoid serious problems from the solar intensity fluctuations. An important effect, pointed out to us initially by R. W. P. Drever, is anisotropic thermal radiation pressure fluctuations acting on the test mass due to a fluctuating temperature difference across the cavity. With three stages of thermal shielding, we estimated that this effect will give noise which increases in amplitude as $f^{-16/3}$ at frequencies below about 10^{-5} Hz.

Another potentially limiting effect is random collisions of residual gas molecules with the test mass. This well-known effect would give roughly 10^{-15} cm/s^2/Hz$^{0.5}$ acceleration noise for a fairly dense 10 kg test mass and 10^{-11} torr pressure. Care is needed in avoiding virtual leaks in the test mass cavity, and some initial warming of the cavity to speed up outgassing may be desirable. Based mainly on the random gas molecule collisions and time-varying spacecraft mass attraction, we are currently using 2×10^{-15} cm/s^2/Hz$^{0.5}$ as the desired error budget level for spurious accelerations over the frequency range from roughly 10^{-5} to 10^{-3} Hz.

For electrical forces, the main problem is charging up of the test mass due to cosmic ray impacts. The charge on the test mass has to be sensed by applying a sinusoidal drive field, and then kept low by injecting the opposite charge. The fluctuations in the test mass potential should be kept below 3×10^{-6} volts/Hz$^{0.5}$ if the stray electric field level in the cavity is 1 volt/meter.

The magnetic susceptibility requirement for the test mass will depend on how low the magnetic field gradient from the spacecraft can be kept. The main fluctuating magnetic force on the test mass is likely to be from the interaction of the fluctuating interplanetary field with the dipole moment induced by the gradient of the spacecraft magnetic field. For a spacecraft magnetic field of 10^{-3} Gauss due to current loops 1 meter from the test mass, and for 3×10^{-3} Gauss/Hz$^{0.5}$ fluctuations in the interplanetary field, the susceptibility requirement for the test mass is roughly 10^{-7}.

The effects of momentum transfer due to cosmic ray impacts also have been considered. Protons with energies below roughly 100 MeV will not reach the test mass, and the energy deposited by higher energy particles will be of this order. For galactic cosmic rays, the directions of arrival are nearly isotropic and the arrival times are random. The resulting fluctuating test mass acceleration level is more than an order of magnitude below our current error budget level. For solar cosmic rays, the flux of particles with energies above 100 MeV is believed to be very low, except at the times of major solar flares. At such times, the momentum transfer to the test masses would be large, and would ruin the usefulness of the data for gravitational wave observations for a day or two. This is the only time we know of when the antenna would not get useful data, except for the possibly weekly spacecraft gravitational potential checks.

5) Expected LAGOS Antenna Performance

Based on the error models discussed above, plus the shot noise limit for 1 Watt of transmitted laser power, the expected antenna sensitivity is given as a function of frequency in Fig. 2. It appears that other sources of noise in measuring the test mass separation can be kept below the shot noise limit at frequencies above 1×10^{-3} Hz. The overall antenna sensitivity curve shown should be regarded as the current goal for the antenna, since a great deal of work is needed in order to determine whether this goal can be achieved within realistic mission constraints. We believe that the most important challenge for such a mission will be achieving a high degree of reliability, despite the need for three separate spacecraft and the requirement of very low spurious acceleration levels for the test masses at frequencies of 10^{-5} to 10^{-3} Hz. However, this must be accomplished within mass constraints of something like 300, 300, and 400 kg for the three spacecraft, in order to keep the mission costs from escalating.

The antenna sensitivity curve shown in Fig. 2 is roughly an order of magnitude below the level of the expected power spectrum of gravitational wave signals from 10^{-5} to 10^{-3} Hz (Hils et al. 1986). These signals are due to a number of types of galactic binaries, including ordinary main-sequence binaries, contact binaries, cataclysmic variables, close white dwarf binaries, and neutron star binaries. Since many such binaries exist in even as narrow a band as 0.1 cycle/year, they generally will not be resolvable except for frequencies near 10^{-3} Hz or higher, where many individual binaries can be observed. Instrumental noise levels can be checked by observing changes in the signal level as the center of the galaxy goes through the nulls in the antenna pattern, and the direction to individual resolved binaries can be determined in the same way. The antenna sensitivity also is sufficient for detecting possible pulses due to the collapse of very massive objects to form black holes near the time of galaxy formation. More information about the observable types of signals will be published soon.

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LASER HETERODYNE GRAVITATIONAL WAVE ANTENNA

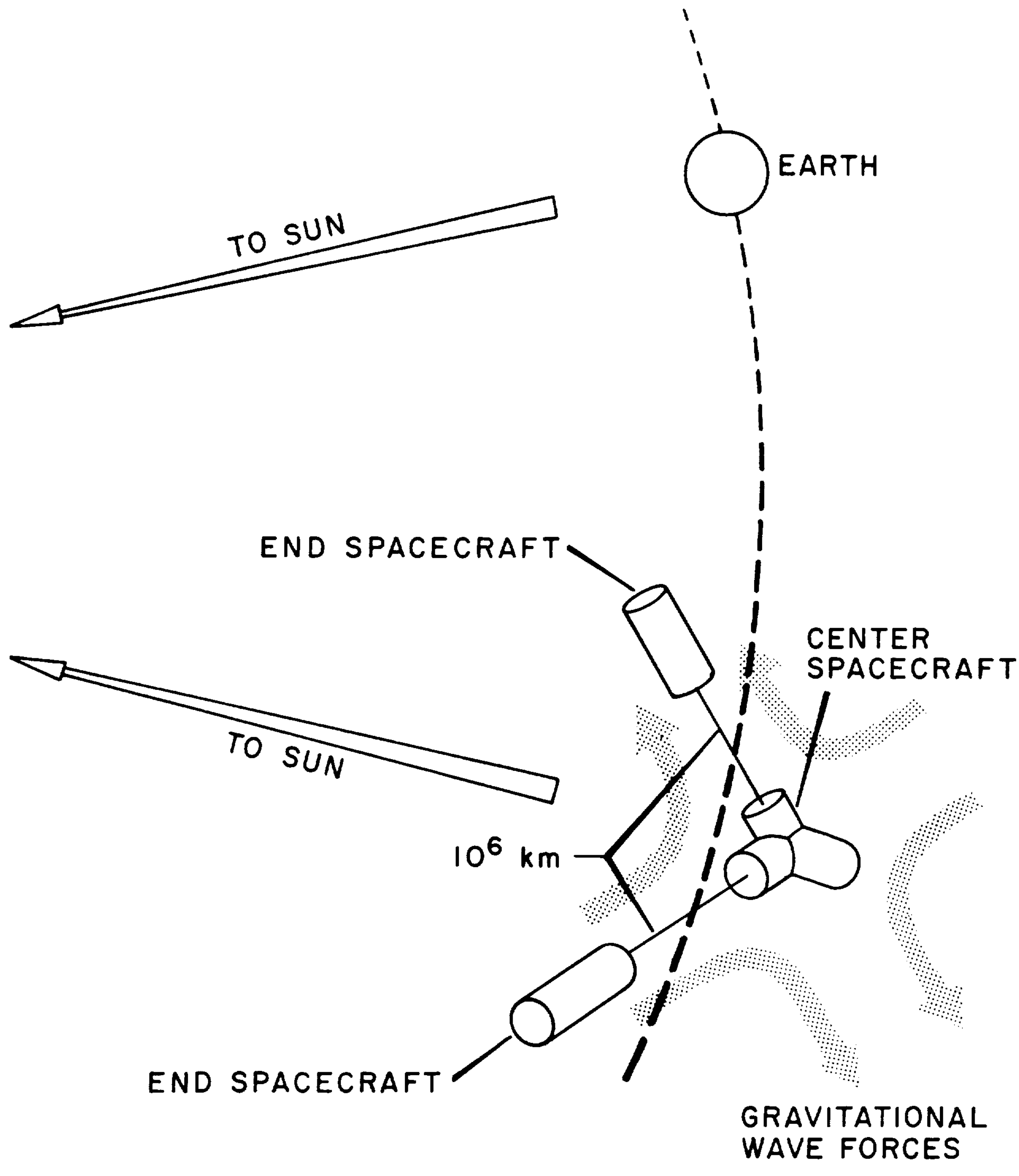

FIG. 1 — Laser Heterodyne Gravitational Wave Antenna

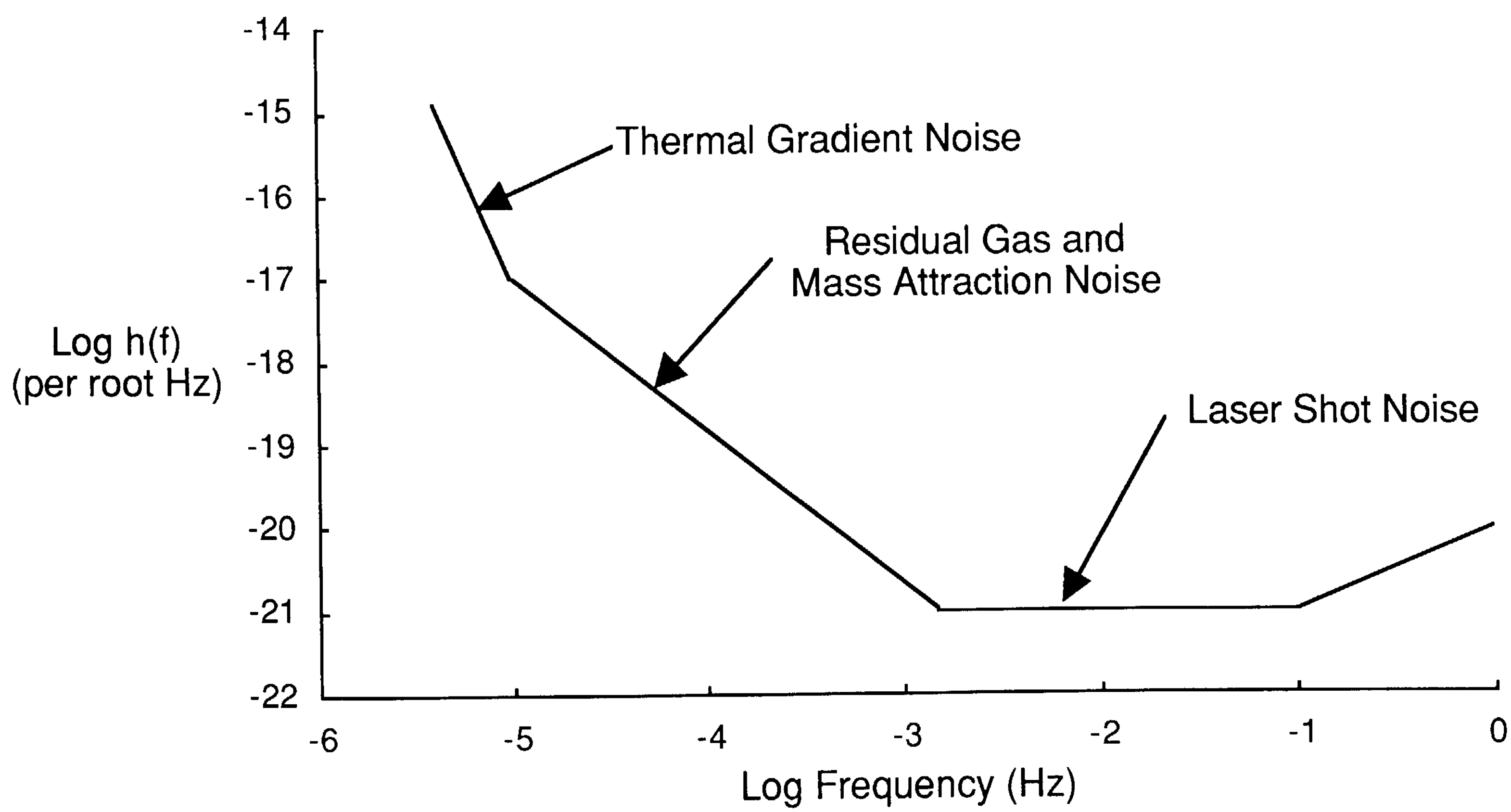

FIG. 2 — Antenna Sensitivity

DISCUSSION

ARMSTRONG: I think it is remarkable that you are talking about confusion-limited vs. flux-limited gravitational wave astronomy, at least at low frequencies!

MATZNER: How active are these satellites? (For instance, to maintain orientation and drag-free behavior.) What is the expected gas consumption rate, and what is the expected lifetime?

BENDER: The expected fuel consumption rate for cold gas thrusters is about 10 grams per day. The mission lifetime would be 10 years.

SHAPIRO: How do you envision obtaining the "geometry" of the system, and its change with time, with sufficient accuracy to acquire fringes with the laser interferometers?

BENDER: We expect to take about a week to determine and refine the spacecraft orbits with the DSN antennas before releasing the test masses and starting the measurements.

CLAUSER: How do you release the proof mass to guarantee no rotation? With 1w of laser power, won't the proof mass charge up quickly? Will the charge be truely uniform on the mass? How do you discharge it?

BENDER: We haven't worked on the release mechanism problem yet. Clearly this is a very sensitive part of the procedure if we use a non-rotating test mass. We plan on having only a small part of the laser power hit the test mass. The main charging mechanism is expected to be cosmic ray impacts. Even using carefully applied gold or other coatings, there will be varying work functions on the surface and some non-uniformity in the charge distribution. The proof mass charge probably would be neutralized by spraying charge onto it.

HELLINGS: What would the sensitivity of your interferometer be if you did not have a drag-free system?

BENDER: The largest spurious accelerations of the spacecraft are expected to be roughly 10^{-11} g. For differing effects on the different spacecraft which are 1% this large and last for a few thousand seconds, the apparent signal would be about 10^{-15}.

SONNABEND: Have you considered reducing the gas pressure variations on the proof mass by a cryogenic housing?

BENDER: Yes. But the cryogen supply would limit the mission length, and the spacecraft is already complicated enough.

SCHUMAKER: (Re. his comment on problem of rapid fringe-rate.) Couldn't you overcome that problem just by using two local oscillators, tuned to compensate for the expected Doppler shifts?

BENDER: Yes, using frequency-offset local oscillators might well be desirable.